

Satellite observations of changes in air quality during the 2008 Beijing Olympics and Paralympics

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[1] For the August–September 2008 Olympic and the Paralympic Games held in Beijing, China, strict controls on pollutant emissions and motor vehicle traffic were imposed on Beijing and neighboring provinces to the South to improve the air quality in and around the city. Satellite measurements over Beijing between July and September showed 43% reductions of tropospheric column nitrogen dioxide, compared to the past three years. When neighboring provinces to the south are included in our analyses, satellite measurements show boundary layer sulfur dioxide reductions of 13% and carbon monoxide reductions of 12% at 700 hPa. Thus, based on satellites observations alone, noticeable reductions in these pollutant tracers were measured during both games. **Citation:** Witte, J. C., M. R. Schoeberl, A. R. Douglass, J. F. Gleason, N. A. Krotkov, J. C. Gille, K. E. Pickering, and N. Livesey (2009), Satellite observations of changes in air quality during the 2008 Beijing Olympics and Paralympics, *Geophys. Res. Lett.*, **36**, L17803, doi:10.1029/2009GL039236.

1. Introduction

[2] In 2001, Beijing, China (40°N, 116°E) won the bid to host the 2008 Olympic (August 8–22, 2008) and Paralympic Games (September 6–17, 2008), hereafter referred to as the Games. Rapid industrialization, economic growth, and urbanization in the past two decades have contributed to the rise of air pollution in China's urban and industrial centers, where photochemical smog and acid deposition are ubiquitous [Fang *et al.*, 2009]. The most recent emissions inventory over Asia by Streets *et al.* [2003] show China is the dominant regional source of anthropogenic sulfur dioxide (SO₂), carbon monoxide (CO), and nitrogen oxide (NO_x = NO + NO₂) emissions largely due to fossil fuel and biofuel use. Streets *et al.* estimates that 45% of total Asian SO₂ emissions in 2000 come from China's coal-fired power plants, with 36% from industrial sources. In the same study, CO and NO_x emission estimates show that China accounts for almost half the total Asian inventory. Zhang *et al.* [2007] noted a 70% increase in China's NO_x emissions between 1995 and 2004, concluding that the accelerated increase is due to the growth in power plant emissions after 2000.

Richter *et al.* [2005] calculate a 42% increase over east central China in tropospheric NO₂ columns during the summer months from 1996 to 2002, based on GOME and SCIAMACHY satellite retrievals.

[3] In an effort to improve Beijing's air quality for the 2008 Games, stringent short-term emission control measures, hereafter referred to as ECMs, were imposed between July and September 2008. This was not the first time pollution control measures have been implemented in Beijing. Wang *et al.* [2007] found that ECMs on vehicular traffic during the Sino-African Summit on November 4–5, 2006 reduced NO_x emissions by 40% in Beijing and proved to be a successful testing ground for the 2008 Games. The same study also found 40%–60% reductions in ground-level aerosol concentrations over the city. However, during the Games Cermak and Knutti [2009] found only modest reductions of 10–15% in total atmospheric aerosols using MODIS aerosol optical thickness measurements, concluding that meteorology and regional particulate levels played a dominant role in determining the aerosol burden over Beijing.

[4] In this study, we present satellite measurements of three major air pollutants in China: NO₂ (a proxy for NO_x), SO₂, and CO. We track their changes before, during, and after the Games from Aura's Ozone Monitoring Instrument (OMI) and Terra's Measurements of Pollutants in the Troposphere (MOPITT) instrument. The three months of sustained ECMs between July and September 2008 provide a unique opportunity to examine the effectiveness of these measures on air quality over the Beijing vicinity and further demonstrate our ability to monitor these changes from space.

2. Emission Control Measures

[5] The Beijing government implemented a series of long- and short-term ECMs, to meet the World Health Organization (WHO) 2000 air quality standard for the duration of the games. The United Nations Environment Program (UNEP) environmental assessment report details the implementation and effectiveness of these control measures [United Nations Environment Program (UNEP), 2009]. Since being awarded the Games in 2001, the Beijing Municipal Government has pursued a range of ECMs. Several prominent long-term pollution-reducing strategies cited in the UNEP report included the building of desulfurization facilities at Beijing's coal fired power plants, the gradual closure of several major emission industries (e.g., Beijing Coke and Chemical Plant, and production lines at Capital Iron and Steel Company), and switching roughly 94% of small coal-burning boilers to cleaner fuels. Leading up to the start of the Olympics (8 August) special short-term

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Figure 1. Map of East-Central China highlighting Beijing (star) and the surrounding provinces affected by the ECMs. Several major industrial cities are included (white circles).

controls were enforced. From 1 July to 20 September, all vehicles that did not meet European exhaust emission standards were prohibited from entering the city, and from 20 July to 20 September 50% of privately owned vehicles were banned from the Beijing area through an odd and even number system [Y. Wang *et al.*, 2009]. To further reduce emissions, power generation facilities operated at 30% capacity, construction activities were suspended and several heavy-polluting factories were targeted to shut down for the duration of both games [UNEP, 2009].

[6] The ECMs were not isolated to Beijing but extended to the highly urbanized industrial and coal-burning sectors in the neighboring provinces, i.e., Tianjin, Hebei, Shandong, Henan, and Shanxi [UNEP, 2009]. These provinces comprise the industrial hub of northeastern China. Figure 1 shows a map of China that highlights our study region encompassing Beijing and the neighboring provinces affected by the ECMs. Details of ECMs applied to the targeted provinces have not yet been released by the Beijing authorities or the Chinese government and are not discussed in the UNEP report; however, satellite measurements show decreases of pollution emissions in those provinces. Several studies have shown that emissions from these provinces significantly impact Beijing's air quality during the summertime when sustained southerly winds are typical [Streets *et al.*, 2007; Y. Wang *et al.*, 2009]. Indeed, between July and September 2008, daily balloon-borne rawinsonde wind data launched at the Beijing International Airport report southerly prevailing winds in the lower troposphere (<700 hPa). Surface temperatures during this period averaged 26°C, with 60% mean relative humidity, and very low surface winds (<3 m/s). Similar meteorological conditions were reported by Y. Wang *et al.* [2009].

3. Satellite Air Quality Data

[7] Tropospheric column NO₂ (^{TC}NO₂) and boundary layer SO₂ (^{BL}SO₂) are measured by OMI, launched in 15 July 2004, onboard NASA's Aura satellite. OMI is a Dutch/

Finnish nadir-viewing hyperspectral imager that provides daily global coverage at a high spatial resolution (13 × 24 km at nadir) capable of mapping pollution products on urban scales. ^{TC}NO₂ is reported as the vertical column density (in molecule/cm²) between the surface and the estimated mean tropopause pressure height of 150 hPa and is interpolated to a horizontal resolution of 0.05° × 0.05° [Bucsela *et al.*, 2006; Wenig *et al.*, 2008]. Bucsela *et al.* [2006] reports retrieval accuracy estimates for the tropospheric column to be 25%, with a precision error of 0.25 × 10¹⁵ molec/cm². The column density of ^{BL}SO₂ (in Dobson units (DU)) = 2.69 × 10¹⁶ molec/cm² is retrieved with the assumption of a center of mass altitude of 0.9 km [Krotkov *et al.*, 2008]. ^{BL}SO₂ is reported at a gridded horizontal resolution of 0.125° × 0.125°. Krotkov *et al.* [2008] show that in NE China, under clear sky, near nadir-viewing angles, the 1-sigma noise is ~1 DU for individual pixels and ~0.3 DU for ~100 km averages. Thus, area averaged ^{BL}SO₂ measurements are sensitive to strong anthropogenic sources and regional pollution [Carn *et al.*, 2007; Krotkov *et al.*, 2008], making it an appropriate product to detect changes over Beijing and provinces affected by the ECMs. All OMI data used in this study have been filtered to remove cloudy scenes and off-nadir viewing directions.

[8] Launched in 1999, the MOPITT instrument onboard NASA's Terra spacecraft makes CO measurements with a thermal and near-IR nadir-viewing gas correlation radiometer. MOPITT has a nadir pixel size of 22 × 22 km and uses a cross-track scan to provide complete global coverage in three days. We use monthly averaged CO mixing ratio profiles reported at a horizontal resolution of 1° × 1° on seven vertical levels for cloud-free scenes [Deeter *et al.*, 2003]. Our study uses the 700 hPa level because MOPITT has little sensitivity to CO within the boundary layer (BL) [Deeter *et al.*, 2003; Emmons *et al.*, 2004]. The data have been additionally filtered to use only those profiles where the fraction of the retrieval based on the a priori is less than 50%. A validation study by Emmons *et al.* [2004] showed a good qualitative agreement with in situ profiles, with a 20% high bias at all levels. The measurement precision above 700 hPa is ~10%. For consistency, we include years 2005 to 2008 to match the OMI data record.

4. Analyses and Discussion

[9] Figure 2 shows that ^{TC}NO₂, ^{BL}SO₂, and CO_{700hPa} are measurably lower over Beijing and neighboring provinces to the south during the Games (August and September 2008) than the average of the past three years. ^{TC}NO₂ reductions (Figure 2a and 2b) are noticeably confined to the urban centers, owing to the relatively short chemical lifetime of ground-level NO₂ (~1 day). In August, ^{TC}NO₂ decreases between 2008 and the 2005–2007 mean are estimated to be 49%, 30%, 26%, 24%, and 16% over Beijing, Tianjin, Shijiazhuang, Handan, and Qinhuangdao, respectively (see Figure 2a for locations). In September, decreases of 36%, 17%, 33%, 19% over Beijing, Tianjin, Handan, and Qinhuangdao, respectively, are observed with a minor decrease of 3% over Shijiazhuang (Figure 2b). The city of Jinan in the Shandong province is the exception showing a slight increase of 3% in August and 22% in September in 2008, relative to 2005–2007. In contrast,

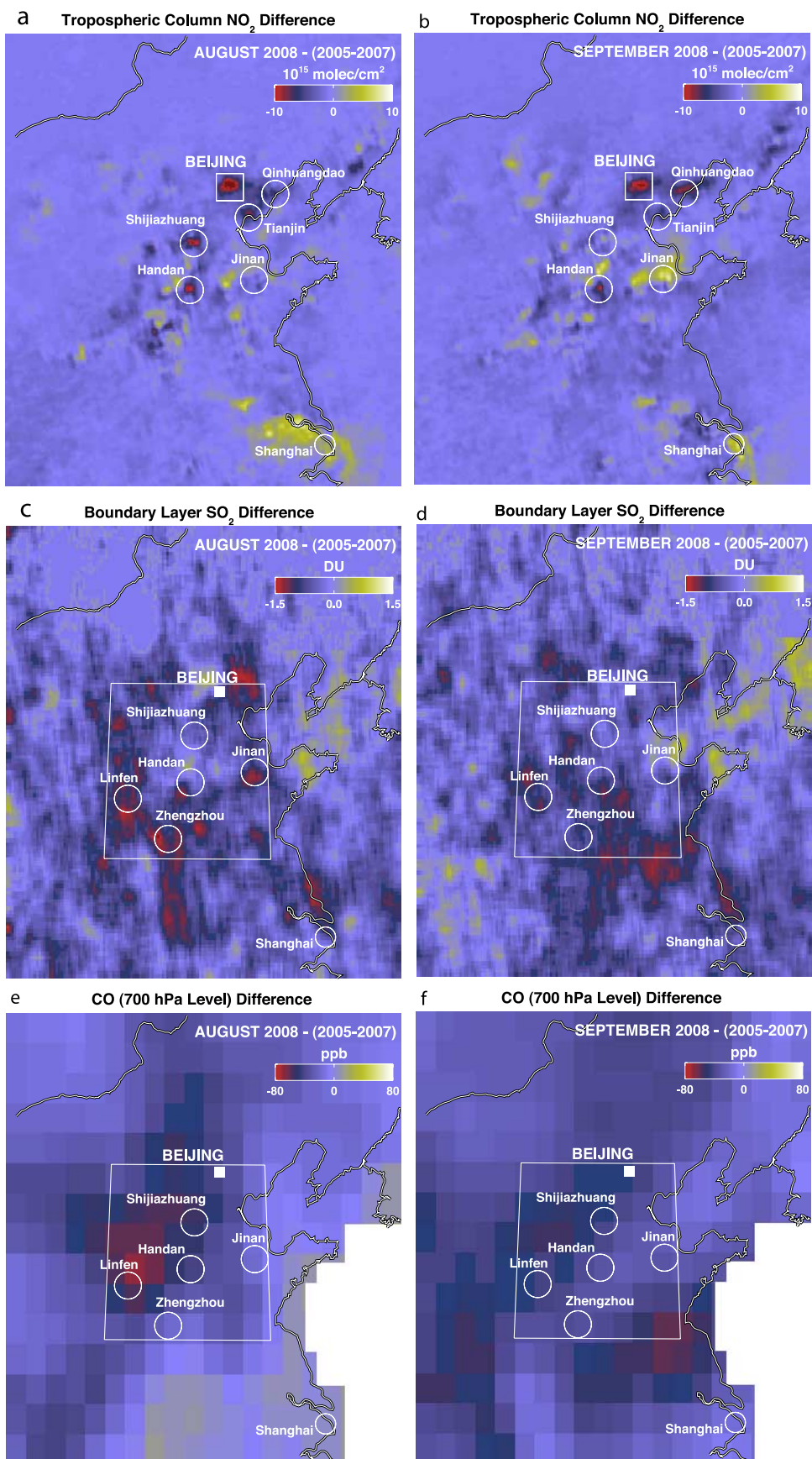


Figure 2

large urban areas further south that have not been affected by the ECMs (i.e., Shanghai and vicinity) show increased $^{\text{TC}}\text{NO}_2$. Overall, OMI detects the largest decreases of $^{\text{TC}}\text{NO}_2$ over Beijing.

[10] Whereas localized urban features are well-resolved by OMI $^{\text{TC}}\text{NO}_2$, maps of $^{\text{BL}}\text{SO}_2$ and $\text{CO}_{700\text{hPa}}$ show rather widespread reductions throughout the emissions controlled region (Figures 2c–2f). In particular, Figures 2b and 2c show that observed $^{\text{BL}}\text{SO}_2$ reduction ‘hotspots’ tend to be offset from major urban centers. OMI and MOPITT retrievals of SO_2 and CO , respectively, are not very sensitive to surface emissions, and as such, tend to measure plumes after they have been vented from the BL. Above the BL, SO_2 and CO have longer chemical lifetimes and, depending on the prevailing meteorology, enhanced measurements may not be close to the emission source. Thus, $^{\text{BL}}\text{SO}_2$ and $\text{CO}_{700\text{hPa}}$ are more representative of regional scale variations of air pollution and intercontinental transport [Krotkov *et al.*, 2008; Brock *et al.*, 2004]. To be quantitative, we define an analysis domain [110° – 119°E , 34° – 40°N] that includes Beijing and neighboring provinces to the south affected by the ECMs (Figures 2c–2f, white box). Within this domain, we calculate regional $^{\text{BL}}\text{SO}_2$ reductions in 2008, relative to 2005–2007, to be 11% in August and 14% in September. Similarly, reductions of $\text{CO}_{700\text{hPa}}$ are estimated to be 17% (August) and 20% (September) within the domain.

[11] Richter *et al.* [2005] showed that local changes in tropospheric NO_2 columns from GOME measurements are proportional to changes in local NO_x emissions. In this study, we use the higher resolution OMI $^{\text{TC}}\text{NO}_2$ measurements to construct the monthly mean time series over Beijing, shown in Figure 3a (top), and the percentage difference relative to each of the past three years Figure 3a (bottom). Note that the $0.5^\circ \times 0.5^\circ$ monthly averages encompass an area slightly smaller than the white box over Beijing seen in Figures 2a and 2b. The most striking feature is the significant decrease in $^{\text{TC}}\text{NO}_2$ between July and September 2008, when vehicular traffic was reduced significantly as part of the ECMs. In the first half of 2008, the variability in $^{\text{TC}}\text{NO}_2$ (Figure 3a, top - black vertical bars) follow mid-point values of around 20×10^{15} molec/ cm^2 , typical of previous years, and decrease dramatically to 8.3×10^{15} molec/ cm^2 in July recording a 42% reduction, relative to 2005–2007. Between July and September 2008, $^{\text{TC}}\text{NO}_2$ was reduced by roughly 43% and the monthly variability during that period was reduced to a standard deviation of 5×10^{15} molec/ cm^2 , compared to the 2005–2007 average of 10×10^{15} molec/ cm^2 for the same months. $^{\text{TC}}\text{NO}_2$ amounts do not return to typical values greater than 15×10^{15} molec/ cm^2 until the ECMs are lifted at the end of September 2008. Y. Wang *et al.* [2009] calculate a 36% reduction of NO_x between August 2008 and 2007 based on in-situ measurements taken downwind of Beijing. In addition, measure-

ments taken by M. Wang *et al.* [2009] within the Beijing city center calculates a 41% decrease in August 2008 compared to the pre-control period before July 20th. Our August 2007–2008 calculations show a 44% reduction in OMI $^{\text{TC}}\text{NO}_2$, consistent with Y. Wang *et al.* [2009] results.

[12] In Figure 3, we plot the monthly mean time series of $^{\text{BL}}\text{SO}_2$ (Figure 3b) and $\text{CO}_{700\text{hPa}}$ (Figure 3c) over the previously defined ECMs domain. $^{\text{BL}}\text{SO}_2$ measurements are excluded in January and February 2008 due to a major snow event that occurred throughout northern China, resulting in erroneously high values of $^{\text{BL}}\text{SO}_2$ due to large retrieval sensitivities to snow/ice. Compared to 2005–2007, OMI measures reductions of $^{\text{BL}}\text{SO}_2$ from July to September 2008 to be 13% (Figure 3b, bottom). The $^{\text{BL}}\text{SO}_2$ precision is greatly improved by averaging over large areas and longer time periods [Krotkov *et al.*, 2008] and we find that the monthly area mean standard deviation between July and September 2008 is small at 0.15 DU ($1-\sigma$), similar to previous years (Figure 3b, vertical bars). Although the extra ECMs ceased in September 2008, the monthly mean $^{\text{BL}}\text{SO}_2$ remains lower on average through the end of the year, relative to 2005–2007. The data suggests that the ECMs applied to the targeted provinces within our domain have resulted in effectively lowering the SO_2 emissions for the longer term. According to the UNEP report, between 2000 and 2006, approximately 200 factories were relocated outside the Beijing area and a number of heavily polluting industries were either closed or renovated to use cleaner fuel, such as natural gas. Confirming this notion of a permanent shift towards improved air quality will involve continued monitoring of OMI $^{\text{BL}}\text{SO}_2$ over the ECMs domain in the coming years.

[13] Monthly mean $\text{CO}_{700\text{hPa}}$ over the ECMs domain in Figure 3c show a similar pattern of persistent low values in the latter half of 2008 relative to the past three years. The period from August to December 2008 mark the lowest set of monthly mean $\text{CO}_{700\text{hPa}}$ mixing ratios since 2005 (Figure 3c, top). Comparing 2008 with the 2005–2007 average, we estimate August and September $\text{CO}_{700\text{hPa}}$ decreases to be 17% and 20%, respectively (Figure 3c, bottom). The $1-\sigma$ standard deviation for the same months is 39 ppb in 2008 and 46 ppb in the 2005–2007 average. The slight increase in July of $\sim 2\%$ is due to increases relative to 2005 and 2006. However, when compared to July 2007, $\text{CO}_{700\text{hPa}}$ decreases by roughly 6%. July 2008 $\text{CO}_{700\text{hPa}}$ observations also show a high degree of variability; almost double the $1-\sigma$ standard deviation, or 23 ppbv higher, than in previous Julys. Between July and September 2008 and the 2005–2007 average, we estimate $\text{CO}_{700\text{hPa}}$ reductions to be roughly 12%. However, if we focus on just the August and September months, when both Games were held, we find $\text{CO}_{700\text{hPa}}$ is reduced by 19% in 2008, compared to the 2005–2007 average. The observed persistent low values of $\text{CO}_{700\text{hPa}}$ within our study region in the latter half of 2008,

Figure 2. Maps of changes in the amount of $^{\text{TC}}\text{NO}_2$ [molecule/ cm^2], $^{\text{BL}}\text{SO}_2$ [DU], and $\text{CO}_{700\text{hPa}}$ mixing ratio in parts per billion [ppbv] for (a, c, and e) August and (b, d, and f) September over northeastern China. Changes in the respective tracers are calculated by subtracting the mean of each month between 2005 and 2007 from the monthly mean in 2008. The large white box (Figures 2c–2f) outlines our ECMs domain, for calculating BL SO_2 and $\text{CO}_{700\text{hPa}}$ reduction estimates. $\text{CO}_{700\text{hPa}}$ data (Figures 2e and 2f) are not shown over the ocean because of anomalous measurements due to changes in MOPITT’s sensitivity to surface temperatures at land-ocean boundaries.

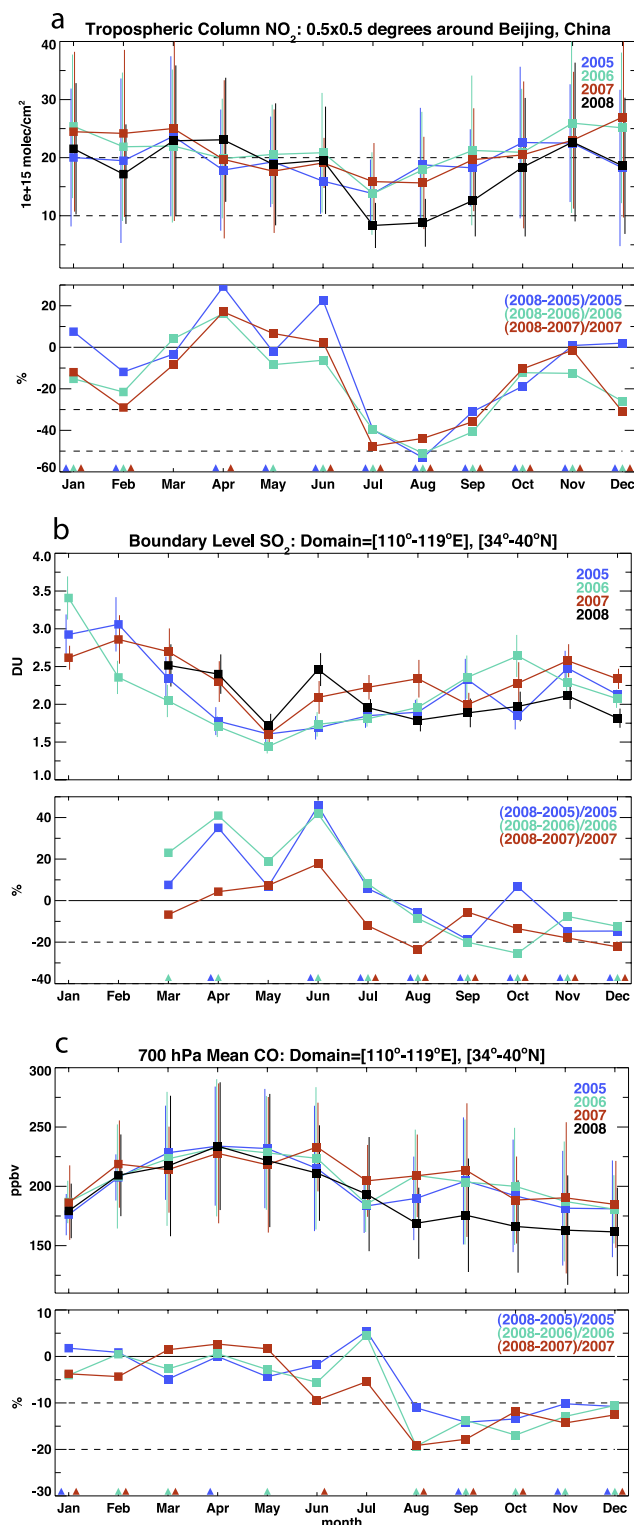


Figure 3. Monthly mean time series of pollutant amounts from 2005 to 2008 for (a) TCNO_2 [molec/cm^2], (b) BLSO_2 [DU] and (c) $\text{CO}_{700\text{hPa}}$ [ppbv]. Vertical bars are the $1\text{-}\sigma$ standard deviation. (bottom) Monthly percentage differences between 2008 and the previous years for the same tracers, respectively. Dashed lines serve to highlight the decreases in the various tracers. The solid triangles indicate the statistical significance of the monthly mean differences between 2008 and previous years using a two-tailed t-test with a 95% confidence interval.

along with the decrease in BLSO_2 , reflect the efficacy of ECMs imposed on industry and power plants in Beijing and the surrounding regions in the long term.

5. Summary

[14] We present a comprehensive space-based assessment of the chemical changes in major gaseous pollutants during the Beijing 2008 Olympic and Paralympic Games. Hosting both events was a major incentive for the Beijing government to adopt stringent measures to control pollution emissions and improve air quality standards in and around the city. The OMI and MOPITT measurements during the stringent ECMs from July through September 2008 show decreases of 43% in TCNO_2 over Beijing, and 13% in BLSO_2 and 12% in $\text{CO}_{700\text{hPa}}$ (19% excluding July) over a wider region, compared to previous years for the same months. Pollutant levels for TCNO_2 returned to normal after the transportation bans were lifted at the end of September. However, we observe a persistent decrease, compared to prior years, in the BLSO_2 and $\text{CO}_{700\text{hPa}}$ monthly means after the short-term controls were lifted. This may be a consequence of regional ECMs implemented on industrial and power plant emissions, in preparation of the Games. It remains to be seen whether these low levels will continue in the future. We conclude that Beijing's ECMs enforced between July and September 2008 successfully lowered the levels of NO_2 , SO_2 and CO during that period, compared to levels normally present over the city and vicinity.

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